Summary of Research and Final Report

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Project Title : An Investigation of the Flow Physics of Acoustic Liners by Direct Numerical Simulation

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This report concentrates on reporting the effort and status of work done on three dimensional (3-D) simulation of a multi-hole resonator in an impedance tube. This work is coordinated with a parallel experimental effort to be carried out at the NASA Langley Research Center. The outline of this report is as follows :

1. Preliminary consideration
2. Computation model
3. Mesh design and parallel computing
4. Visualization
5. Status of computer code development

1. Preliminary Consideration

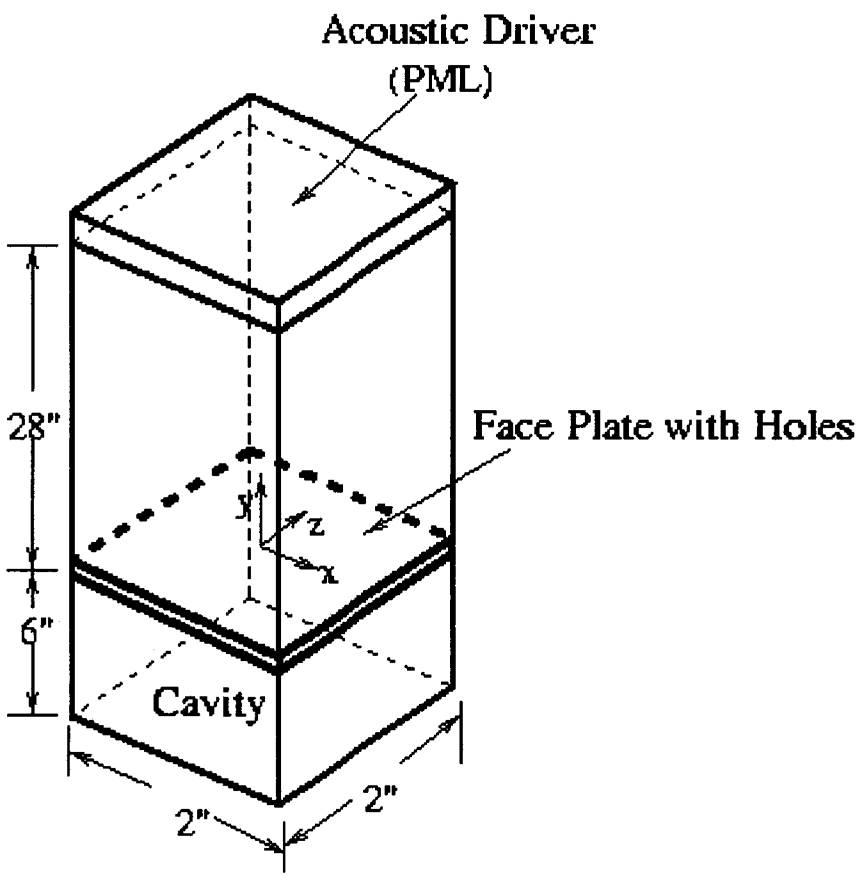


Figure 1. Dimensions of impedance tube.

Figure 1 shows the dimensions of the impedance tube the flow and acoustic fields of which are to be simulated numerically. The face plate has six hole patterns arranged in such a way that if the walls are mirrors the holes inside the impedance tube is but a small part of an infinitely large hole pattern of an acoustic liner.. A simple estimate of the number of mesh points needed for a 3-D simulation reveals that an extraordinarily large number of points is required. It is about two orders of magnitude more than a 2-D simulation. The computer run time too is much longer. For these reasons, a careful preliminary study is important to avoid making a wrong move that might require great remedial effort later.

It is clear at the outset, the use of just a few computer processors as is in the case of 2-D simulations would be totally inadequate. The computer run time needed would be far too long even for a research project. Massively parallel computing is a necessity. At the Florida State University, two massively parallel computers are available. The University has a SP-3 and a SP-4 IBM parallel computer. The SP-4 is a much faster and larger machine. It has 512 processors (CPUs) arranged in 16 nodes each having 32 CPUs. Since this is a university computer, it cannot be run as a completely dedicated machine for this project. On considering that job queuing is most likely required after a job is submitted and that it is easier to obtain allocation for one node than two or more, it is decided to design the computer code to run on one node (32 CPUs) with the possibility of using two nodes (64 CPUs) when such a need arises. Based on this decision, all the computer codes of this project are designed primarily **to run on 32 processors.**

Table 1. Computer Requirements — Preliminary Estimate

Sample		1	2	3	4	5	6
Number of holes		1	2	4	8	16	32
Length of hole (inch)		2	1	0.5	0.25	0.125	0.0625
Estimated number of mesh points required		2.36×10^7	2.36×10^7	2.36×10^7	1.83×10^7	1.58×10^7	7.89×10^6
Computation time (days) per period	One processor	26.3	26.3	26.3	20.5	13.2	6.6
	32 processors at 70% efficiency	1.18	1.18	1.18	0.92	0.6	0.3
Computer memory required		4G	4G	4G	3G	2G	1G

Note: Each processor of the FSU-SP4 computer has 1G memory (G: Gigabite). Each node has 32 processors.

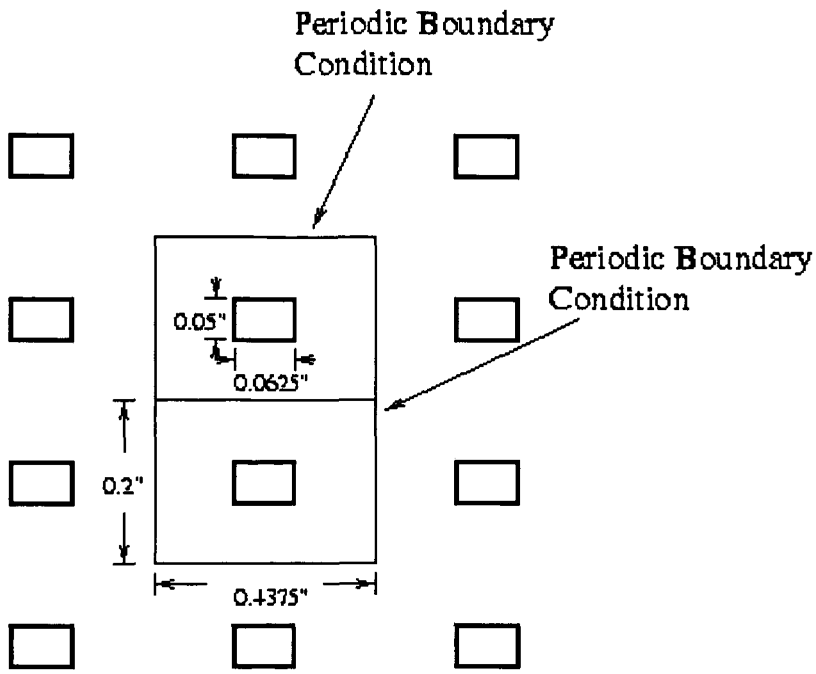
There are six samples each with a unique hole pattern. Because it is necessary to resolve the viscous scale adjacent to the walls of a hole, very small size meshes are required in the volume occupied by the hole. It follows that a significant fraction of the total number of mesh points of the computation ends up being used to fill the volume of space around the hole. Since the hole size of the six samples is different, it is decided that it is **not feasible to develop a single computer code for all six samples. Computationally, it would be more efficient if a special mesh design and computer code is developed for each case.** We believe that this is a prudent and effective approach for the project.

The periodic pattern of the holes in each of the six samples allows the use of periodic boundary conditions. This is important for it allows the numerical simulation to concentrate on a single hole alone. This offers an enormous saving of mesh points. Table 1 shows a preliminary estimate of the number of mesh points requires, the computer memory needed and the anticipated clock time per cycle (assuming the input sound has a frequency of 2.5 KHz) for the simulation of each sample. It is clear from this table that sample 6, having the smallest size hole, has the least memory and shortest run time requirements. For this reason, all our current efforts are devoted to simulating sample 6 with the hope that the experience gain would facilitate the simulation of the other five samples.

2. Computation model

In performing numerical simulation, the 3-dimensional compressible Navier-Stokes equations are to be solved. For the present acoustic liner problem, viscous effect is important only near the openings of the resonators. To resolve the unsteady viscous Stokes layer, very fine meshes must be used. Away from the hole opening, compressibility effect dominates. Hence a much coarser mesh resolution would be sufficient. Thus in the computation model, it is assumed that the viscous terms of the Navier-Stokes equations are needed only in the two regions with the smallest size mesh. Outside these two regions, the Euler equations are solved instead. For time marching computation, the 7-point stencil Dispersion-Relation-Preserving (DRP) scheme will be used. Artificial selective damping will be added. The DRP scheme is a very accurate CAA algorithm. It can resolve waves using no more than 7 to 8 mesh points per wave length. To treat the multi-scale nature of the problem efficiently, the multi-size-mesh multi-time-step version of the DRP scheme is implemented. There is a significant saving of computer memory and run-time in using the multi-mesh-size and multi-time step features of the method.

As mentioned before, the periodic boundary conditions will be implemented in the computation. The periodic boundary conditions reduce the size of the computation domain enormously. However, periodic boundary conditions require strict symmetry of the flow and acoustic fields with respect to the planes on which periodic boundary conditions are imposed. In reality, such strict symmetry is never attained. Thus we regard the periodic boundary conditions as a good approximation. Experience with two dimensional simulation of the flow fields of slit resonators, suggests that due to the nonlinearity of the problem, the flow is always slightly chaotic and non-symmetric, although, in principle, they could be totally symmetric. In order to allow the simulation to be slightly chaotic and nonsymmetric, a decision is made to simulate not just one hole but two adjacent holes for sample 6. The slightly chaotic and non-symmetric flow and acoustic field will definitely affect the interaction between neighboring holes. Simulating two holes will, therefore, allow us to assess quantitatively the lack of strict symmetry on hole-hole interaction. Figure 2 shows the plan view of the computation domain. The research plan is to perform numerical simulation of one hole with periodic boundary conditions all around and then repeat the simulation for two holes. We hope to detect the effect of chaotic motion on hole-hole interaction by comparing the results of the two runs, one with one hole and the other with two holes.

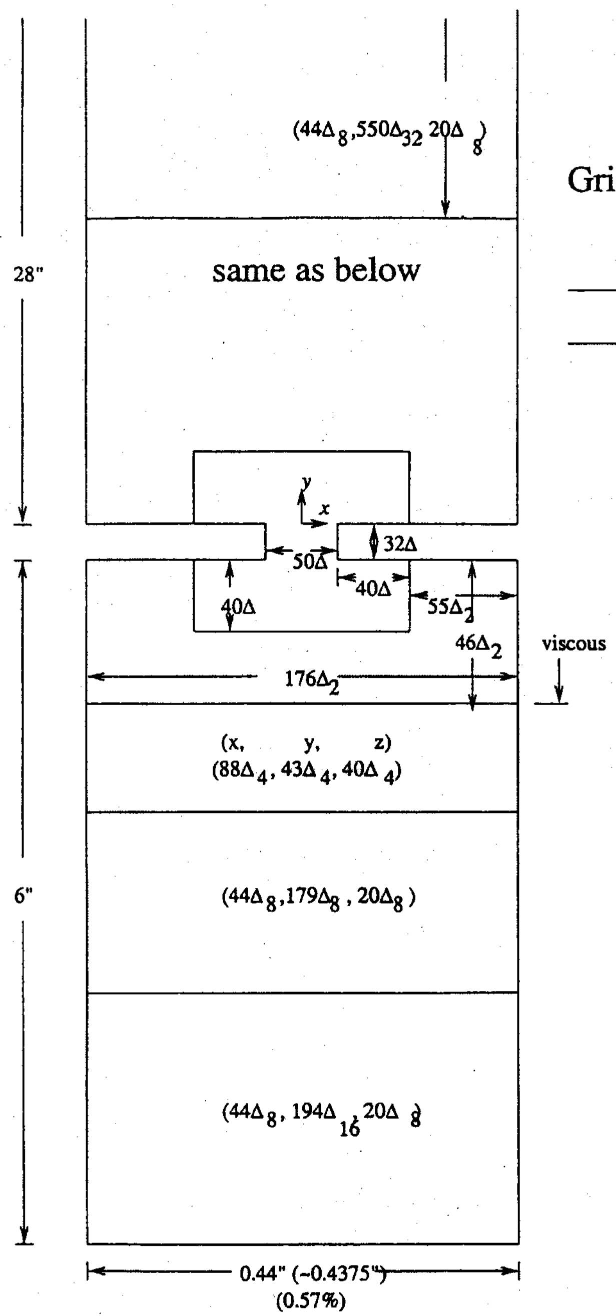


The grid is designed for 32 processors.

Figure 2. Plan view of computation domain for Sample 6.

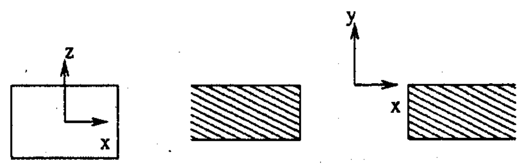
3. Grid design and parallel computing

For the 7-point stencil DRP scheme, the resolved range in wavenumber space is $\alpha\ \Delta x = 0.8$, where α is the wave number. It is easy to show, based on the highest resolved wave number being $\alpha\ \Delta x = 0.8$ and standard formula for the structure of the Stokes layer, that the use of Δx=0.00125″ would be sufficient to compute



Sample 6 Grid (x-y section)

Grid points (one hole):	CPUs
Δ: 1798465	11
Δ2: 1155222	4
Δ4: 321112 Δ8: 1229445	1



top view side view

Figure 3. Mesh design in the x-y plane

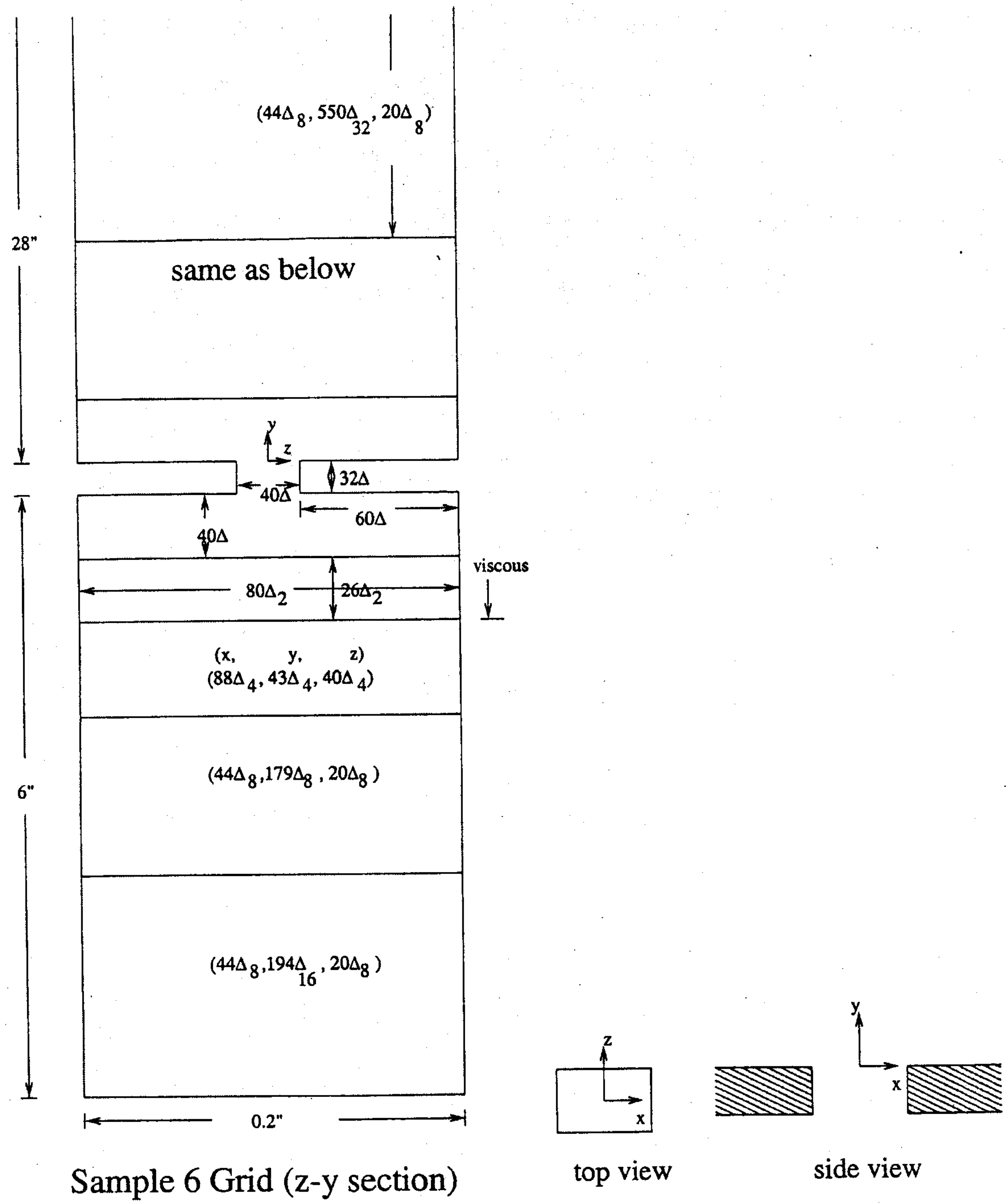


Figure 4. Mesh design in the y-z plane

accurately the unsteady Stokes layer at 3 KHz frequency. This is taken to be the smallest mesh size, Δ, used in all our simulations. The mesh design for a single hole of sample 6 in the x-y plane is as shown in figure 3. The mesh design in the y-z plane is shown in figure 4. There are altogether 4.5 million mesh points ; 9 millions when two holes are considered. Of this total, about 1.8 million are points with mesh size Δ, 1.16 million of mesh size 2Δ, 0.3 million of mesh size 4Δ and 1.23 million of mesh size 8Δ, 16Δ and 32Δ. To obtain load balance, 11 CPUs are assigned to computations using the finest mesh (mesh size Δ). 4 CPUs are assigned to points with mesh size 2Δ and 1 CPU for the remaining. 32 CPUs will, therefore, be used for a two-hole simulation.

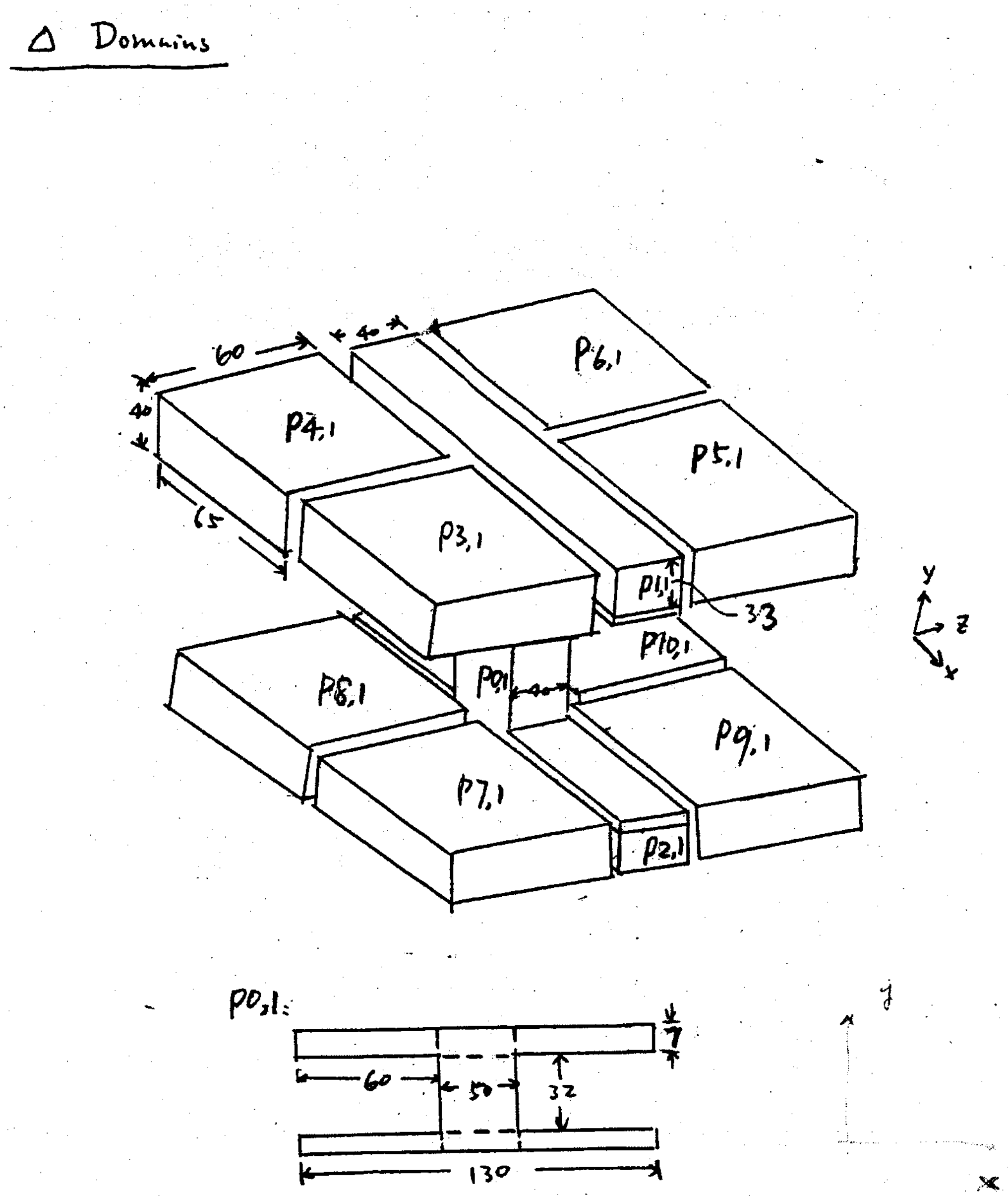


Figure 5. CPU assignment for the finest mesh

$\Delta 2$ Domains

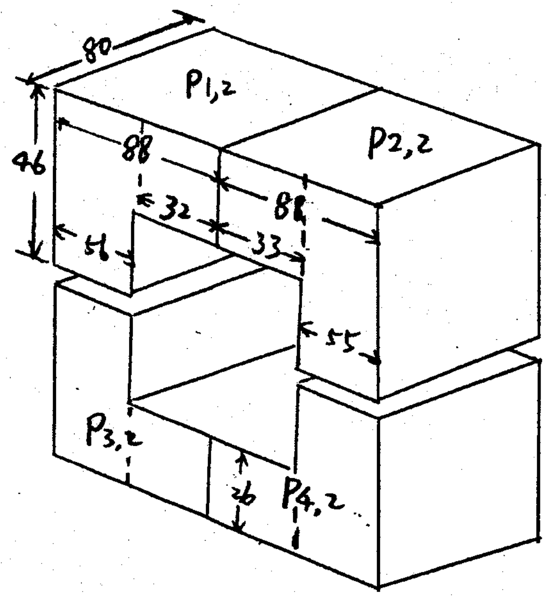


Figure 6. CPU assignment for the mesh points with mesh size 2Δ.

Figure 5 shows the computation domain assigned to each of the 11 CPUs in the finest mesh size region. Figure 6 shows the assigned computational domain for the 4 CPUs in the region with mesh size 2Δ. This distribution of CPUs is based on a best estimate of the work load for points inside the volume as well as additional work load at mesh-size-change interface. For a computation involving a large volume, the additional surface work load is fairly small relative to that in the bulk volume as is in the present case. We believe that for the proposed CPU assignment, the work load of each processor should be about equal. Thus our parallel computation should be quite close to perfect load balance.

In arriving at the final mesh design, both memory and time step requirements have been carefully examined and evaluated. A numerical stability analysis had also been carried out. Based on all these considerations, we conclude that the mesh design should lead to fairly efficient computations.

4. Visualization

With 9 million mesh points in use, an enormous set of space-time data would inevitably be generated by each computer run. We would like to take advantage of the availability of these data sets to better understand the underlying physics and mechanisms by which acoustic energy is being dissipated by the resonant liner. This is, in addition to computing gross acoustic liner properties such as reactance and resistance. To do so, a way to process and display the enormous volume of data must be developed. Technically, this falls into the computation area called "visualization".

We have very little experience in visualization. We have discussed this need with a FSU colleague who is an expert in this field. However, the problem under consideration is not straightforward even to an expert. Thus we will devote some effort to learn and to perform data visualization when we start generating numerical results.

There are several questions in visualization we need answers and decisions relatively quickly. The first one is what variable to display and look at. Should we use density which will produce a scalar field ? Should we concentrate on velocity and/or vorticity ? These are vector fields. As to displaying the data, we would need to decide whether to simply display 2-D cross-sections or 3D light projections or use other alternatives.

5. Status of computer code development.

A computer code for sample 6 including two neighboring holes as shown in figure 2 is being developed. This is a parallel computing code using MPI. The code is specifically designed to run on 32 processors (1 node of the FSU SP-4 parallel computer). Steady progress has been made in programming the code, despite the complexity of the mesh design. For large computer code with thousands of lines, frequent testing of individual subroutine and subprograms becomes absolutely necessary. We expect to continue the programming and testing efforts. We estimate that the code should be ready for actual simulation and data collection by the end of February 2004.